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Evaluation of WC-10Ni thermal spray coating with shot peening on the fatigue strength of AISI 4340 steel.

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Abstract

Fatigue failure is a result of a crack initiation and propagation, in consequence of a cyclical load. In aeronautical components as landing gear the fatigue strength is an important parameter to be considered in project, as well as the corrosion and wear resistance.

The thermal sprayed HVOF technology it's normally used to protect components against wear and corrosion, and are being considerate an alternative to replace chromium by the aeronautical industry. With respect to fatigue life, the HVOF technique induces residual stress on the interface. In the case of tensile residual stresses, the initiation and propagation phases of fatigue process are accelerated; on the other hand, compressive residual stresses close to the surface may increase fatigue life. The technique to improve the coated materials fatigue strength is the shot peening process, which induces residual stress in the surface in order to delay the nucleation and propagation process.

The aim of present study is to compare the influence of WC-10 Ni coating applied by HVOF on the fatigue strength of AISI 4340 steel, with and without shot peening. S-N curves were obtained in axial fatigue tests for material base, and tungsten carbide coated specimens. © 2010 Published by Elsevier Ltd. Open access under [CC BY-NC-ND license](http://creativecommons.org/licenses/by-nc-nd/3.0/).

Keywords: Shot peening, Residual stress; 4340 Steel; Fatigue; HVOF process

1. Introduction

The study of fatigue strength is an important parameter to be considered in components subject to constant variable amplitude loadings.[1] In aircraft industry nucleation and propagation of fatigue cracks are some of the most important consideration in the mechanical properties of metals [2].

Coating materials deposited in the surface of metals has been extensively used in aerospace, automotive and oils fields, in order to improve the corrosion and wear resistance. Chromium plating is used to obtain high hardness, resistance to wear and corrosion, although problems concerning about chromium electroplating application, has been resulting in search to indentify some alternatives to replace the method [3,4]. It's well known that chromium plating has adverse health and negative environmental effects [3]. With respect to mechanical properties, the

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chromium electroplating process drop the fatigue strength, attributed to high tensile stress and microcracks density contained into coating [5].

As surface treatments the shot peening process is indicated to improve the fatigue life, due to tensile residual stress induced. The shot peening process prevent the fatigue cracks initiation, and delay the propagation of fatigue crack, by inducing compressive residual stress field in the superficial layers of substrate [6].

Considered a good alternative to replace galvanic chromium deposits, the thermal spray coatings deposited by HVOF (High Velocity Oxygen Fuel), has been considered a promissory alternative. Recent studies investigated that the influence of HVOF process on the fatigue life reached better results in relation to chromium electroplating performance. Voorwald and co- authors showed that AISI 4340 steel WC-10Ni thermal spray coated, the fatigue strength for 10^5 cycles was 950 MPa, and decreased for 500MPa for hard Chromium electroplated. In the same study it was also observed that for WC-10Ni thermal spray coated specimens better corrosion resistance and higher abrasive wear resistance with lower wear weight than electroplated chromium [5].

The effectiveness of shot peening process to restore the fatigue strength of base material chromium electroplated is shown [4] for low cycle, high cycle and fatigue limit. The shot peening treatment with steel and ceramic shots resulted in the rotating bending fatigue strength of AISI 4340 steel chromium electroplated up to level of base material without chromium [7].

It was also shown that peening using ceramic shots presented lower scatter in fatigue data than steel shots.

In the present paper the influence of shot peening treatment on the axial fatigue strength of AISI 4340 steel WC - 10Ni HVFO thermal spray coated, will be evaluated. In order to study the influence of residual stresses on fatigue life, the stress field was measured by an X-ray tensometry.

Scanning electron microscopy was used to investigate the fatigue source appearance.

2. Experimental Procedure

2.1. Materials and mechanical properties

The coatings studied in this work were Cr3C2–25NiCr and WC-10Ni, deposited on a steel substrate using a high-velocity oxy-fuel system (HVOF). The chemical composition of AISI 4340 steel is represented on the table 1.

Table 1. – Chemical composition of AISI 4340

Element %	C	S	Mn	Cr	Ni	Mo
Specification	0,38-0,43	0,25 máx.	0,60-0,80	0,70-0,90	1,65-2,00	0,20-0,30
Current	0,41	0,24	0,73	0,8	1,74	0,25

Mechanical properties obtained by means of quenching from 845°C during 45 minutes, cooled in oil (20°C) followed by double tempering process in the range 230±5°C for 4 hours, are shown in the table 2.

Table 1 – Mechanical properties of AISI 4340 Steel

Hardness (HRc)	50 – 52
Ultimate Tensile Strength (MPa)	1864
Yield Tensile Strength (MPa)	1514

2.2. Axial fatigue specimens

The test specimen used for the axial fatigue tests in figure 1 was machined from hot-rolled, quenched and tempered bars, according to ASTM E466.

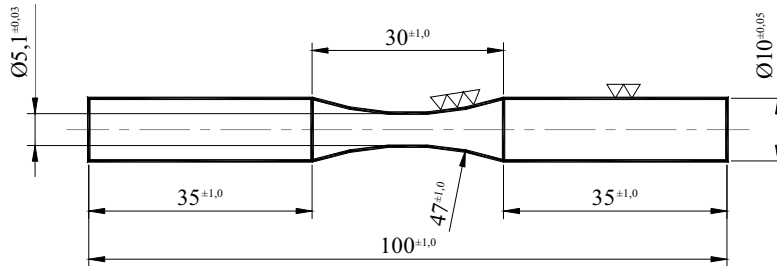


Fig. 1. Axial fatigue testing specimen.

The specimen surface was prepared for thermal spray coating by grit blasting with aluminum oxide mesh 90 to enhance adhesion. Fatigue tests were conducted using a sinusoidal load of 10 Hz frequency and load ratio of $R=0,1$, at room temperature. Experimental tests consider as fatigue strength the complete fracture of the specimen or 10^7 load cycles. Four groups of fatigue specimens were prepared to obtain S-N curves for axial fatigue tests:

- 15 smooth specimens of base material;
- 12 smooth specimens of base material with shot peening;
- 10 smooth specimens of base material with WC-10Ni thermal spray coated by HVOF process, 200 μ m thick;
- 14 smooth specimens of base material shot peened and WC-10Ni thermal spray coated by HVOF process, 200 μ m thick.

2.3. HVOF thermal spray processing

Coatings were deposited using a HVOF torch, model JP-5000, HOBART-TAFA Technologies. The spraying parameters used for WC-10Ni is shown in the table 3.

Table 3 – HVOF application parameters

Spray Distance	150 – 300 mm
Density	4,8 g/cm ³ , according to ASTM B-212
Deposition velocity	900 m/s
Deposition rate	50 μ m/min

2.4. Residual stress measurement

The X-ray diffraction method was used to determine the residual stress field induced by the thermal spray coatings. The absolute values of the residual stresses were measured by “GURTEQ – Non Destructive Testing” with RAYSTRESS® equipment that use X-ray diffraction method. The equipment characteristics are [9]: Ψ goniometer geometry, Cr-K radiation and registration of {221} diffraction lines. The accuracy of the stress measurement was $\Delta\sigma=\pm 20$ MPa. In order to obtain the stress distribution by depth, the layers of specimens were removed by electrolytic polishing with a nonacid solution.

2.5 Shot peening

The S-N curves were obtained for base metal and shot peened AISI 4340 steel. The shot peening parameters used were:

- intensity: 0,006-0,010 A
- S230 steel shot
- out put flux: 3kg
- velocity: 250 mm/min
- distance: 200mm
- rotation: 30 rpm
- 120% covering

The process was performed before blasting with aluminum oxide, according to standard SAE-AMS-S-13165.

3. Results and discussion

The coating hardness was determined with a microhardness testing system using a Vickers diamond indenter on the top surface of polished cross sections and represented in figure 2 for WC-10Ni coating. To perform the indentation, a load of 100g was used and maintained for 15s.

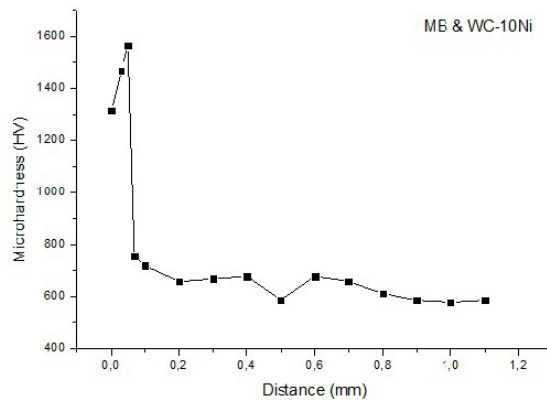


Fig. 2. Vickers Microhardness 100g. WC-10Ni.

Figure 2 shows lower values near the coating surface, increasing until a maximum close to the interface, decreasing again at interface coating substrate. From figure 2 it may be observed that the thickness of the coating was kept around 150µm. The work-hardening effects, which resulted from the fact that the thermal spray coated specimens were blasted to enhance adhesion, may be related to the increase in hardness near the interface coating-substrate [9].

3.1 Axial fatigue results:

The S-N curves for the axial fatigue tests for the base metal and WC-10Ni thermal spray coated , are represented in Fig 3.

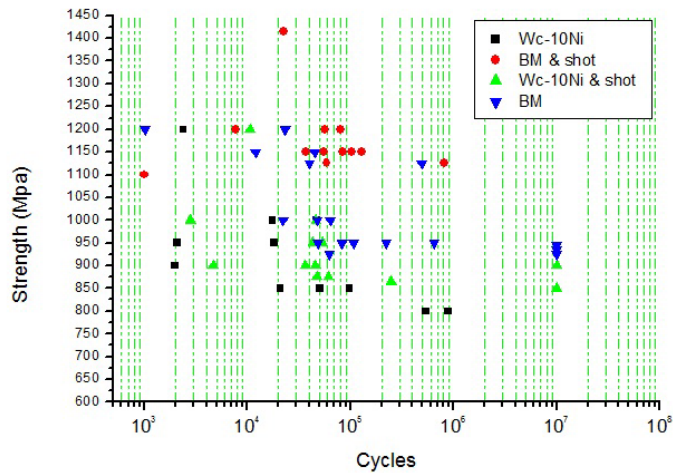


Fig. 3. S-N curves for axial fatigue tests.

The S-N curves represented in the figure 2, indicates the effect of HVOF coating on the fatigue strength reduction of AISI 4340 steel, comparing to base metal. The presence of tensile residual stresses which are relieved by HVOF coating microcracking during application and crack growth through interface inside substrate, were the factor tha decrease de fatigue strength. The shot peening process was effective to increase the base metal and de coated material fatigue strength. Compressive residual stresses at surface and inside substrate played an important role to avoid or delay fatigue crack nucleation and propagation.

3.2. Residual stress

The results of residual stress analysis are demonstrated in table 4 and 5.

Table 4 indicates residual internal stresses for AISI 4340 steel base material and after shot-peening.

Table 4 – Residual Internal Stresses

Material	Depth (mm)		
	0,00	0,10	0,20
AISI 4340 steel	+150	+75	0
AISI 4340 steel & Shot peening	-330	-630	-170

Tensile residual stresses were obtained for AISI 4340 steel base material at surface and 0,10mm from the surface. High compressive residual stresses are observed on the specimen surface for shot peened AISI 4340 steel. The residual stress profile shows compressive stress at 0,10mm from surface and tendency to decrease in value with increase in the depth.

The residual stresses for base material WC-10Ni thermal spray coated and base material shot peened and WC-10Ni thermal spray coated by HVOF process. 200µm thick, are indicated in table 5.

Table 5 – Residual Stresses WC-10Ni

N	Depth (mm)	MPa	MPa
		AISI 4340 WC-10Ni	AISI 4340 WC-10Ni & Shot peening
1	0,00	30	-400
2	0,02	-	-580
3	0,04	-	-500
4	0,07	-	-270
5	0,10	50	-130
6	0,13	-	+150
7	0,16	-	+170
8	0,20	0	+150

As indicated in tables 4 and 5, the HVOF thermal spray process reduced the tensile residual stresses on the specimen surface (0,00mm depth), from 150 MPa to 30 MPa. Compressive residual stresses are formed from mechanical deformation during particle impact. The tensile shrinkage stresses of the coating are associated to the fast cooling and solidification as particles strike the surface. According to experimental data from table 2, the through thickness residual stresses for shot peened AISI 4340 steel WC-10Ni thermal spray coated, changed from compressive to tensile inside coating, with maximum compressive stresses at 0,02mm depth. From table 2 it is also possible to observe that the shot peening process changed residual stresses from tensile to compressive until c. a. 0,10mm depth.

3.3. Scanning electronic microscopy

Figures 4 and 5 represent the fractures surface for the WC-10Ni thermal sprayed without shopeening and shot peened, respectively.

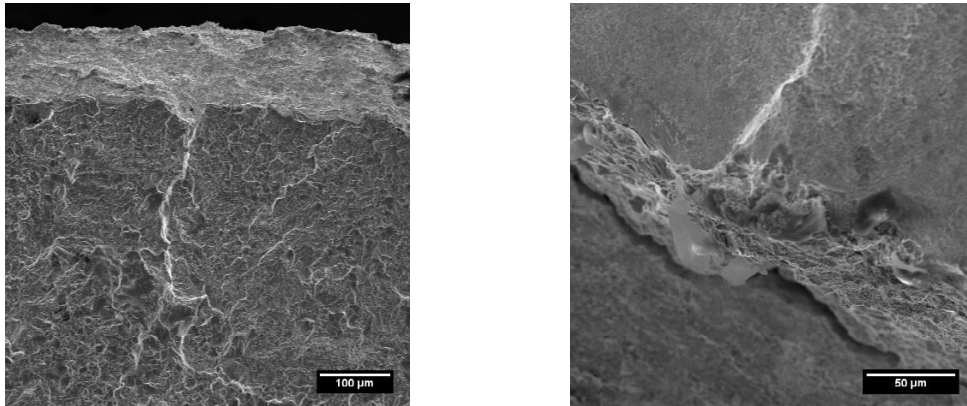


Fig. 4. Fracture surface of axial fatigue specimen coated by WC-10Ni (a) 200x, (b) 500x

Fig. 4 shows the fracture surfaces from axial fatigue specimens WC-10Ni thermal spray coated. It is possible to observe the coating homogeneity, strong interface substrate/coating and microcracks density distributed along thickness in a radial shape, and show fatigue cracks initiation and propagation at interface coating /substrate.

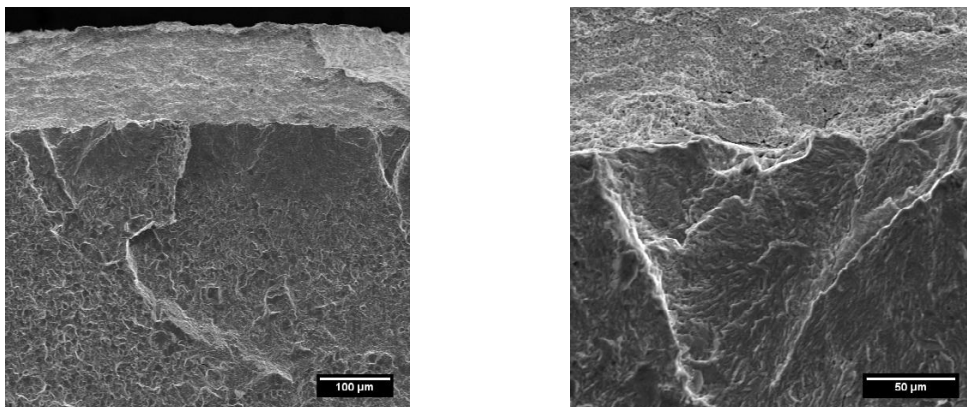


Fig. 5. Fracture of axial fatigue specimen coated by WC-10Ni shot peened (a) 200x (b) 500x

The effect of shot peening in delay or avoid the crack nucleation and propagation it's shown in Fig. 5. Compressive residual stresses at interface coating/ substrate were effective to avoid or delay fatigue crack nucleation and growth. The residual stresses profile played as a barrier against crack propagation.

4. Conclusions

- The work-hardening effects may be related to the increase in hardness near the interface WC-10Ni coating/ AISI 4340 steel substrate;
- For WC-10Ni thermal spray coated material shot peened the fatigue strength was restored, reaching results close to base material;
- The HVOF thermal spray process reduced the tensile residual stresses on base metal specimen surface. The through thickness residual stresses for shot peened AISI 4340 steel WC-10Ni thermal spray coated changed from compressive to tensile inside coating, with maximum compressive stresses at 0,02mm depth;
- The shot peening process increased the axial fatigue strength of AISI 4340 steel WC-10Ni thermal spray coated specimens. The fatigue limit increased 13,3% from 750MPa to 850MPa.

5. Author Artwork

Gilson Silva Junior is a material engineer, member of Fatigue and Aeronautical Materials Research Group DMT/FEG/UNESP, Guaratinguetá, Brazil.

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